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6. AUTHORS

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14. ABSTRACT

The control of quantum dynamics is a field that spans a wide variety of applications in physics, chemistry,biology and other domains. The techniques to achieve control, currently used and proposed for the future, are as diverse as the applications. Despite this diversity, our research aims to show a high degree of fundamental commonality between quantum control procedures spanning all application domains. This requires the development of new mathematical tools at the intersection of quantum probability and quantum physics. Our

15. SUBJECT TERMS

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Prescribed by ANSI Std. Z39.18

Report Title

Final Report: Control of Quantum Open Systems: Theory and Experiment

ABSTRACT

The control of quantum dynamics is a field that spans a wide variety of applications in physics, chemistry,biology and other domains. The techniques to achieve control, currently used and proposed for the future, are as diverse as the applications. Despite this diversity, our research aims to show a high degree of fundamental commonality between quantum control procedures spanning all application domains. This requires the development of new mathematical tools at the intersection of quantum probability and quantum physics. Our research is also developing new ideas in quantum control, specifically in topics that are presently in their infancy. Of particular importance is perhaps the most pressing quantum control frontier: real-time coherent feedback control of non-Markovian open systems.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/23/2017	4	Walter Vinci, Daniel A. Lidar. Optimally Stopped Optimization, Phys. Rev. Applied, ( ): . doi:
01/23/2017	5	Tameem Albash, Daniel A. Lidar. Adiabatic Quantum Computing, Rev. Mod. Phys., ( ): . doi:
02/03/2017	6	Shunji Matsuura, Hidetoshi Nishimori, Walter Vinci, Tameem Albash, Daniel A. Lidar. Quantum annealing correction at finite temperature: ferromagnetic p-spin models, Phys. Rev. A, ( ): . doi:
11/11/2016	2	Tameem Albash, Walter Vinci, Daniel A. Lidar. Simulated-quantum-annealing comparison between all-to-all connectivity schemes, Physical Review A, ( ): . doi:
11/11/2016	1	Walter Vinci, Tameem Albash, Daniel A Lidar. Nested quantum annealing correction, npj Quantum Information, ( ): 16017. doi:

TOTAL: **5**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1.11/16 Physics Colloquium, University of Calgary
2.08/16 Workshop on Future Directions in Quantum Information Processing, sponsored by the Basic Research Office of the Assistant Secretary of Defense for Research and Engineering, BRICC, Arlington, VA
3.08/16 Semi-Quantum Computing workshop, Institute for Quantum Computing, Waterloo, Canada
4.05/16 Physics Colloquium, Caltech
5.03/16 Distinguished Speaker, Science and Engineering of Quantum Information Systems (SEQIS) Seminar Series, Sandia National Lab, Albuquerque, NM
6.03/16 Annual meeting of the American Physical Society, session on “Adiabatic Quantum Computation and Quantum Annealing: Energy Landscapes, Speedup and Embedding”, Baltimore, MD
7.03/16 Annual meeting of the American Physical Society, Invited Session (B13) on “Adiabatic Quantum Computation and Quantum Annealing”, Baltimore, MD
8.01/16 Quantum Computing Panel member for Caltech Physics Club
9.01/16 Scalable Superconducting Quantum Information Technology (SCALEQIT) International Conference,Delft, Netherlands
10.12/15 US – Japan Workshop on New-Generation Computers: Quantum Annealing and Coherent Computing, Stanford, CA
11.11/15 QuICS Seminar, University of Maryland, College Park, MD
12.10/15 participant at IARPA-QEO proposers workshops, Washington, DC

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
Joshua Job	0.38
Huo Chen	0.25
Siddharth Muthu Krishnan	0.25
Milad Marvian	0.25
FTE Equivalent:	**1.13**
Total Number:	**4**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
Daniel Lidar	0.16
FTE Equivalent:	**0.16**
Total Number:	**1**

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Scientific Progress and Accomplishments

- Simulated-quantum-annealing comparison between all-to-all connectivity schemes: In this project, we considered ways in which Quantum annealing aims to exploit quantum mechanics to speed up the search for the solution to optimization problems. Most problems exhibit complete connectivity between the logical spin variables after they are mapped to the Ising spin Hamiltonian of quantum annealing. To account for hardware constraints of current and future physical quantum annealers, methods enabling the embedding of fully connected graphs of logical spins into a constant-degree graph of physical spins are therefore essential. Here, we compared the recently proposed embedding scheme for quantum annealing with all-to-all connectivity by Lechner, Hauke, and Zoller (LHZ) [Sci. Adv. 1, e1500838 (2015)] to the commonly used minor embedding (ME) scheme. Using both simulated quantum annealing and parallel tempering simulations, we found that for a set of instances randomly chosen from a class of fully connected, random Ising problems, the ME scheme outperformed the LHZ scheme when using identical simulation parameters, despite the fault tolerance of the latter to weakly correlated spin-flip noise. This result persisted even after we introduced several decoding strategies for the LHZ scheme, including a minimum-weight decoding algorithm that resulted in substantially improved performance over the original LHZ scheme. We explained the better performance of the ME scheme in terms of more efficient spin updates, which allowed it to better tolerate the correlated spin-flip errors that arose in our model of quantum annealing. Our results left open the question of whether the performance of the two embedding schemes could be improved using scheme-specific parameters and new error correction approaches. Ref: Phys. Rev. A 94, 022327 (2016). In collaboration with MURI participants Walter Vinci and Tameem Albash.

- Nested quantum annealing correction: In this project, we presented a general error-correcting scheme for quantum annealing that allowed for the encoding of a logical qubit into an arbitrarily large number of physical qubits. Given any Ising model optimization problem, the encoding replaced each logical qubit by a complete graph of degree C, representing the distance of the error-correcting code. A subsequent minor-embedding step then implemented the encoding on the underlying hardware graph of the quantum annealer. We demonstrated experimentally that the performance of a D-Wave Two quantum annealing device improved as C grows. We showed that the performance improvement can be interpreted as arising from an effective increase in the energy scale of the problem Hamiltonian or, equivalently, an effective reduction in the temperature at which the device operates. The number C thus allowed us to control the amount of protection against thermal and control errors, and, in particular, to trade qubits for a lower effective temperature that scales as C-¿, with ¿¿2. This effective temperature reduction is an important step towards scalable quantum annealing. Ref: Nature Quant. Info. 2, 16017 (2016). In collaboration with MURI participants Walter Vinci and Tameem Albash.

- Optimally Stopped Optimization: In this project, we combined the fields of heuristic optimization and optimal stopping. We proposed a strategy for benchmarking randomized optimization algorithms that minimized the expected total cost for obtaining a good solution with an optimal number of calls to the solver. To do so, rather than letting the objective function alone define a cost to be minimized, we introduced a further cost-per-call of the algorithm. We showed that this problem can be formulated using optimal stopping theory. The expected cost is a flexible figure of merit for benchmarking probabilistic solvers that can be computed when the optimal solution is not known, and that avoids the biases and arbitrariness that affect other measures. The optimal stopping formulation of benchmarking directly leads to a real-time, optimal-utilization strategy for probabilistic optimizers with practical impact. We applied our formulation to benchmark simulated annealing on a class of MAX2SAT problems. We also compared the performance of a D-Wave 2X quantum annealer to the HFS solver, a specialized classical heuristic algorithm designed for low tree-width graphs. On a set of frustrated-loop instances with planted solutions defined on up to N = 1098 variables, the D-Wave device is two orders of magnitude faster than the HFS solver, and, modulo known caveats related to suboptimal annealing times, exhibits identical scaling with problem size. Ref: Phys. Rev. Applied 6, 054016 (2016). In collaboration with MURI participant Walter Vinci.
- Error suppression for Hamiltonian-based quantum computation using subsystem codes: In this project, we presented general conditions for quantum error suppression for Hamiltonian-based quantum computation using subsystem codes. This involved encoding the Hamiltonian performing the computation using an error detecting subsystem code and the addition of a penalty term that commutes with the encoded Hamiltonian. The scheme was general and included the stabilizer formalism of both subspace and subsystem codes as special cases. We derived performance bounds and showed that complete error suppression resulted in the large penalty limit. To illustrate the power of subsystem-based error suppression, we introduced fully 2-local constructions for protection of the swap gate of adiabatic gate teleportation and the Ising chain in a transverse field. Ref: Phys. Rev. Lett. 118, 030504 (2017). In collaboration with MURI participant Milad Marvian.
- Quantum annealing correction at finite temperature: ferromagnetic p-spin models: The performance of open-system quantum annealing is adversely affected by thermal excitations out of the ground state. While the presence of energy gaps between the ground and excited states suppresses such excitations, error correction techniques are required to ensure full scalability of quantum annealing. Quantum annealing correction (QAC) is a method that aims to improve the performance of quantum annealers when control over only the problem (final) Hamiltonian is possible, along with decoding. Building on our earlier work [S. Matsuura et al., Phys. Rev. Lett. 116, 220501 (2016)], we study QAC using analytical tools of statistical physics by considering the effects of temperature and a transverse field on the penalty qubits in the ferromagnetic p-body infinite-range transverse-field Ising model. We analyze the effect of QAC on second (p=2) and first (p=3) order phase transitions, and construct the phase diagram as a function of temperature and penalty strength. Our analysis reveals that for sufficiently low temperatures and in the absence of a transverse field on the penalty qubit, QAC breaks up a single, large free-energy barrier into multiple smaller ones. We find theoretical evidence for an optimal penalty strength in the case of a transverse field on the

penalty qubit, a feature observed in QAC experiments. Our results provide further compelling evidence that QAC provides an advantage over unencoded quantum annealing. Ref: Phys. Rev. A 95, 022308 (2017). In collaboration with MURI participant Walter Vinci and Tameem Albash.

- Adiabatic Quantum Computing: Adiabatic quantum computing (AQC) started as an approach to solving optimization problems, and has evolved into an important universal alternative to the standard circuit model of quantum computing, with deep connections to both classical and quantum complexity theory and condensed matter physics. In this review we give an account of most of the major theoretical developments in the field, while focusing on the closed-system setting. The review is organized around a series of topics that are essential to an understanding of the underlying principles of AQC, its algorithmic accomplishments and limitations, and its scope in the more general setting of computational complexity theory. We present several variants of the adiabatic theorem, the cornerstone of AQC, and we give examples of explicit AQC algorithms that exhibit a quantum speedup. We give an overview of several proofs of the universality of AQC and related Hamiltonian quantum complexity theory. We finally devote considerable space to Stoquastic AQC, the setting of most AQC work to date, where we discuss obstructions to success and their possible resolutions. To be submitted to Reviews of Modern Physics. Ref: arXiv: 1611.04471. In collaboration with MURI participant Tameem Albash.

Technology Transfer

Status: Pending
Title: Quantum Enhanced Optimization
Source of Support: IARPA
Period of Performance: Base: 02/1/2017 – 01/31/2020; Option: 02/1/2020 – 01/31/2022
Award Amount: $45,219,035 (Lidar’s portion (average $1,702,027 per year))